New experimental limit on Pauli Exclusion Principle violation by electrons (the VIP experiment)

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Abstract. The Pauli exclusion principle (PEP) represents one of the basic principles of modern physics and, even if there are no compelling reasons to doubt its validity, it still spurs a lively debate, because an intuitive, elementary explanation is still missing, and because of its unique stand among the basic symmetries of physics. A new limit on the probability that PEP is violated by electrons was estabilished by the VIP (VIolation of the Pauli exclusion principle) Collaboration, using the method of searching for PEP forbidden atomic transitions in copper. The preliminary value, $\frac{1}{2}\beta^2 < 4.5 \times 10^{-28}$, represents an improvement of about two orders of magnitude of the previous limit. The goal of VIP is to push this limit at the level of 10^{-30}.

1. Introduction

The Pauli exclusion principle (PEP), which plays a fundamental role in our understanding of many physical and chemical phenomena, from the periodic table of elements, to the electric conductivity in metals, to the degeneracy pressure (which makes white dwarfs and neutron stars stable), is a consequence of the spin-statistics connection [1]. Although the principle has been spectacularly confirmed by the number and accuracy of its predictions, its foundation lies deep in the structure of quantum field theory and has defied all attempts to produce a simple proof, as nicely stressed by Feynman [2]. Given its basic standing in quantum theory, it seems appropriate to carry out precise tests of the PEP validity and, indeed, mainly in the last 15-20 years, several experiments have been performed to search for possible small violations [3, 4, 5, 6, 7, 8]. Often,

these experiments were born as by-products of experiments with a different objective (e.g., dark matter searches, proton decay, etc.), and most of the recent limits on the validity of PEP have been obtained for nuclei or nucleons.

In 1988 Ramberg and Snow [9] performed a dedicated experiment, searching for anomalous X-ray transitions, that would point to a small violation of PEP in a copper conductor. The result of the experiment was a probability $\frac{\beta^2}{2}<1.7\times10^{-26}$ that the PEP is violated by electrons. The VIP Collaboration set up an improved version of the Ramberg and Snow experiment, with a higher sensitivity apparatus [10]. Our final aim is to lower the PEP violation limit for electrons by at least 4 orders of magnitude, by using high resolution Charge-Coupled Devices (CCDs), as soft X-rays detectors [11, 12, 13, 14, 15], and decreasing the effect of background by a careful choice of the materials and sheltering the apparatus in the LNGS underground laboratory of the Italian Institute for Nuclear Physics (INFN).

In the next sections we describe the experimental setup, the outcome of a first measurement performed in the Frascati National Laboratories (LNF) of INFN in 2005, along with a brief discussion on the results and the foreseen future improvements in the Gran Sasso National Laboratory (LNGS) of INFN.

2. The VIP experiment

The idea of the VIP (VIolation of the Pauli Exclusion Principle) experiment was originated by the availability of the DEAR (DAΦNE Exotic Atom Research) setup, after it had successfully completed its program at the DAΦNE collider at LNF-INFN [16]. DEAR used Charge-Coupled Devices (CCD) as detectors in order to measure exotic atoms (kaonic nitrogen and kaonic hydrogen) X-ray transitions. CCD's are almost ideal detectors for X-rays measurement, due to their excellent background rejection capability, based on pattern recognition, and to their good energy resolution (320 eV FWHM at 8 keV in the present measurement).

Experimental method The experimental method, originally described in [9], consists in the introduction of new electrons into a copper strip, by circulating a current, and in the search for X-rays resulting from the forbidden radiative transition that occurs if one of the new electrons is captured by a copper atom and cascades down to the 1s state already filled by two electrons with opposite spins. The energy of this transition would differ from the normal K_α transition by about 300 eV (7.729 keV instead of 8.040 keV) [17], providing an unambiguous signal of the PEP violation. The measurement alternates periods without current in the copper strip, in order to evaluate the X-ray background in conditions where no PEP violating transitions are expected to occur, with periods in which current flows in the conductor, thus providing "fresh" electrons, which might possibly violate PEP.

The VIP setup The VIP setup consists of a copper cylinder with 45 mm radius, 50 μm thickness, 88 mm height, fig. 1. surrounded by 16 equally spaced CCDs of type 55 made by EEV [18]. The CCDs are at a distance of 23 mm from the copper cylinder, grouped in units of two chips, one above the other. The setup is enclosed in a vacuum chamber, and the CCDs are cooled to about 168 K by the use of a cryogenic system. The current flows in the thin cylinder made of ultrapure copper foil at the bottom of the vacuum chamber. The CCDs surround the cylinder and are supported by cooling fingers which are projected from the cooling heads in the upper part of the chamber. The CCDs readout electronics is just behind the cooling fingers; the signals are sent to amplifiers on the top of the chamber. The amplified signals are read out by ADC boards in the data acquisition computer. More details on the CCD-55 performance, as well on the analysis method used to reject background events, can be found in reference [16, 19]. A schematic view of the setup is shown in fig. 2.

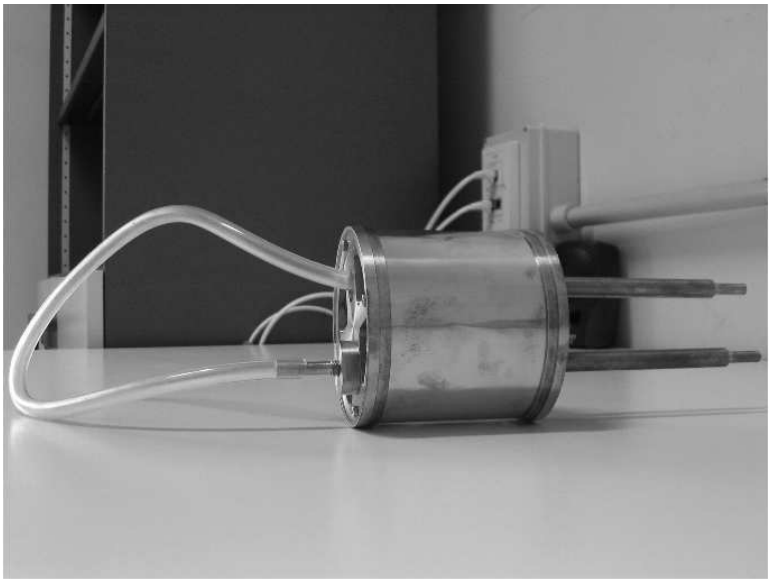

Figure 1. The VIP copper target.

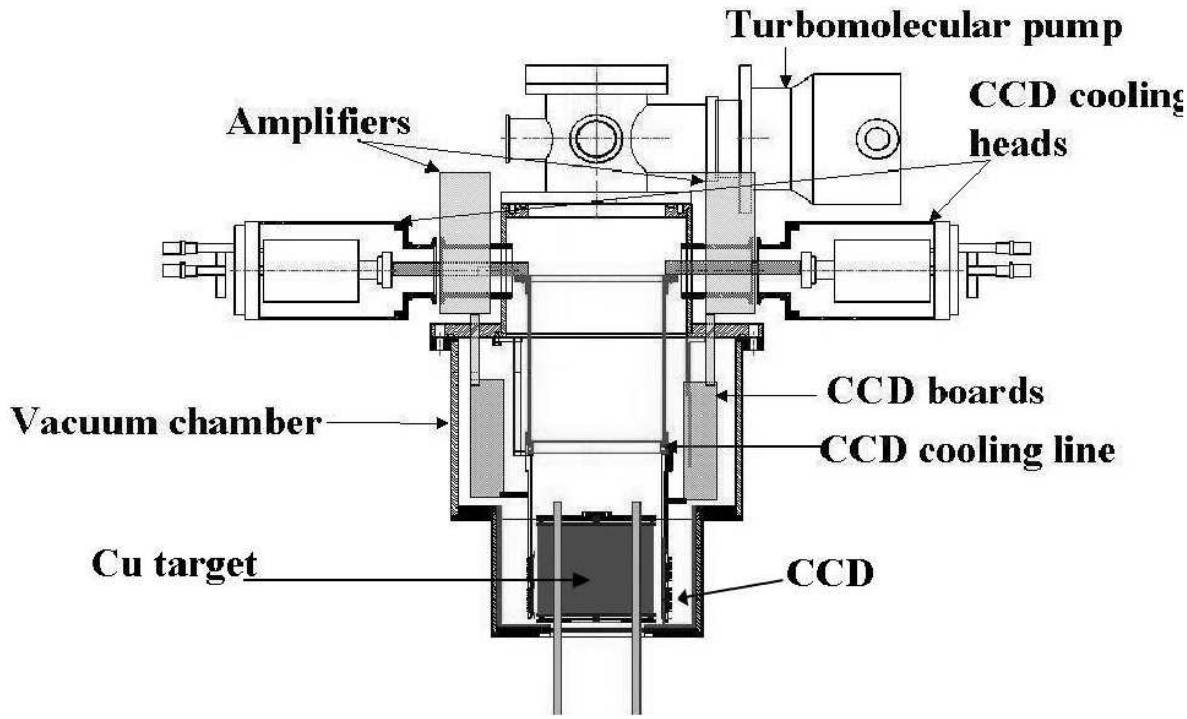

Figure 2. The VIP setup - schematic view

3. First VIP experimental results

The VIP setup is presently taking data in the low-background Gran Sasso underground laboratory of INFN. Before installation in the Gran Sasso laboratory, it was first prepared and tested in the LNF-INFN laboratory, where measurements were performed in the period 21 November - 13 December 2005. Two types of measurements were performed:

- 14510 minutes (about 10 days) of measurements with a 40 A current circulating in the copper target;
- 14510 minutes of measurements without current.

CCDs were read-out every 10 minutes. The resulting energy calibrated X-ray spectra are shown in figure 3. These spectra include data from 14 CCD's out of 16, because of noise problems in

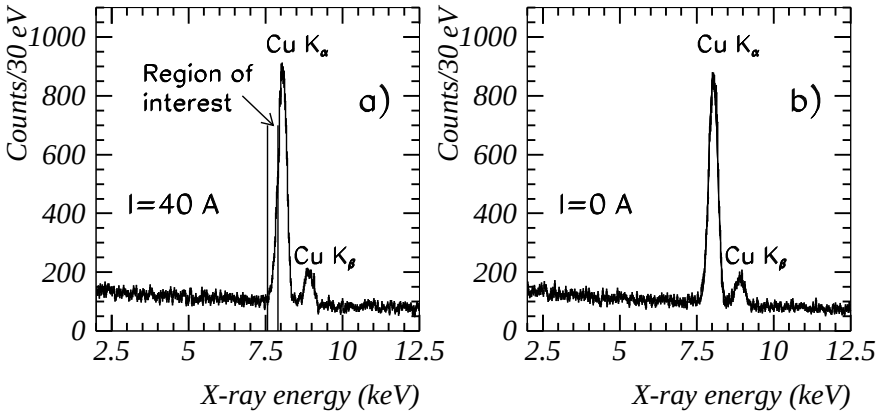

Figure 3. Energy spectra with the VIP setup in laboratory: (a) with current (I = 40 A); (b) without current (I = 0).

the remaining 2. Both spectra, apart of the continuous background component, display clear Cu K_α and K_β lines due to X-ray fluorescence caused by the cosmic ray background and natural radioactivity. No other lines are present and this reflects the careful choice of the materials used in the setup, as for example the high purity copper and high purity aluminium, the last one with K-complex transition energies below 2 keV. The subtracted spectrum is shown in Figure 4 a) (whole energy scale) and b) (a zoom on the region of interest). Notice that the subtracted spectrum is normalized to zero within statistical error, and is structureless. This not only yields an upper bound for a violation of the Pauli Exclusion Principle for electrons, but also confirms the correctness of the energy calibration procedure.

To determine the experimental limit on the probability that PEP is violated for electrons, $\frac{\beta^2}{2}$, from our data, we used the same arguments of Ramberg and Snow: see references [9] and [20] for details of the analysis. The obtained value is:

$$\frac{\beta^2}{2} < 4.5 \times 10^{-28} \qquad at \quad 99.7\% \quad CL. \tag{1}$$

We have thus improved the limit obtained by Ramberg and Snow by a factor about 40.

4. Conclusions and perspectives

The paper reports a new measurement of the Pauli Exclusion Principle violation limit for electrons, performed by the VIP Collaboration at LNF-INFN. The search of a tiny violation was based on a measurement of PEP violating X-ray transitions in copper, under a circulating 40 A current. The new limit for the PEP violation for electrons which was found: 4.5×10^{-28}, is lowering by about two orders of magnitude the previous one [9].

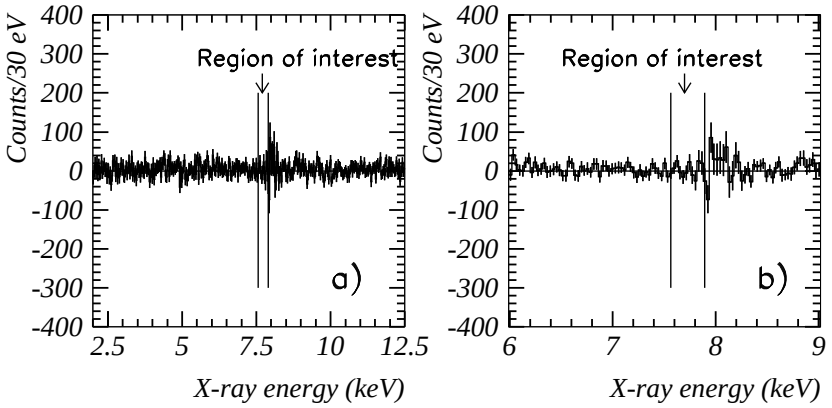

Figure 4. Subtracted energy spectra in the Frascati measurement, current minus no-current, giving the limit on PEP violation for electrons: a) whole energy range; b) expanded view in the region of interest (7.564 - 7.894 keV). No evidence for a peak in the region of interest is found.

We shall soon improve this limit with the measurement in the LNGS-INFN underground laboratory (see figures 5 and 6), at higher integrated currents. From preliminary tests, it results that the X-ray background in the LNGS environment is an order of magnitude lower than in the Frascati Laboratories. A VIP measurement of two years (one with current, one without current) at LNGS, started in Spring 2006, will bring the limit on PEP violation for electrons into the 10^{-30} region, which is of particular interest [21] for all those theories related to possible PEP violation coming from new physics.

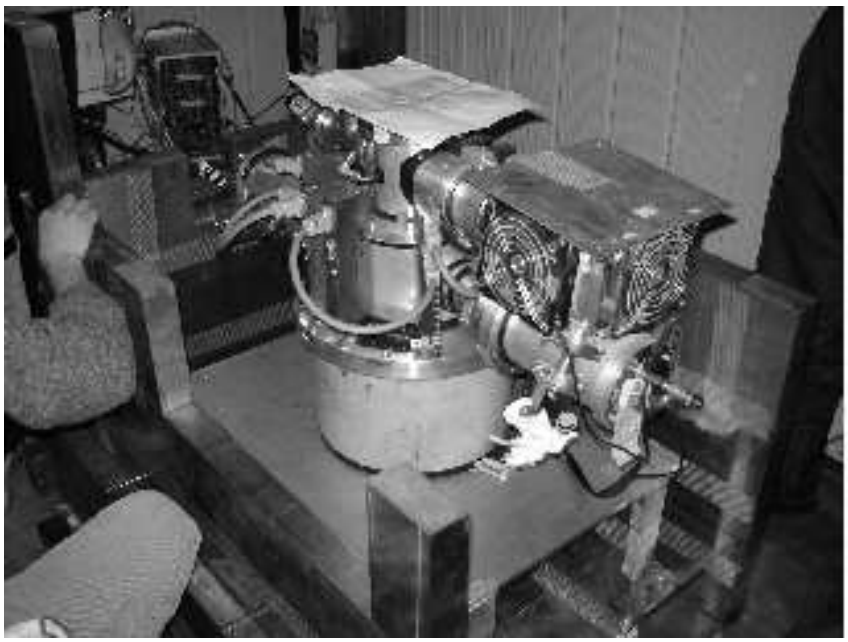

Figure 5. Installation of the VIP setup in Gran Sasso underground laboratory

Figure 6. The VIP setup taking data at the Gran Sasso underground laboratory

[1] W. Pauli 1940 *Phys. Rev.* **58** 716
[2] R. P. Feynman, R. B. Leighton and M. Sands 1963 *The Feynman Lectures on Physics*, Addison-Wesley, Reading, MA
[3] R. Bernabei et al. 1997 *Phys. Lett. B* **408** 439
[4] Borexino Colaboration, H. O. Back et al. 2005 *Eur. Phys. J.* **C37** 421
[5] R. C. Hilborn and C. L. Yuca 1996 *Phys. Rev. Lett.* **76** 2844
[6] Nemo Colaboration 2000 *Nucl. Phys. B (Proc. Suppl.)* **87** 510
[7] E. Nolte et al. 1991 *J. Phys. G: Nucl. Part. Phys.* **17** S355
[8] Y. Tsipenyuk, A. Barabash, V. Kornoukhov and B. Chapyzhnikov 1998 *Radiat. Phys. Chem.* **51** 507
[9] E. Ramberg and G. A. Snow 1990 *Phys. Lett. B* **238** 438
[10] The VIP proposal, LNF-LNGS Proposal, september, 2004, http://www.lnf.infn.it/esperimenti/vip.
[11] J. L. Culhane 1990 *Nucl. Instrum. Methods A* **310** 1
[12] J.-P. Egger, D. Chatellard and E. Jeannet 1993 *Particle World* **3**, 139
[13] G. Fiorucci et al. 1990 *Nucl. Instrum. Methods A* **292** 141
[14] D. Varidel et al. 1990 *Nucl. Instrum. Methods A* **292** 147
[15] R. P. Kraft et al. 1995 *Nucl. Instrum. Methods A* **372** 372
[16] T. Ishiwatari et al. 2004 *Phys. Lett. B* **593** 48; G. Beer et al. 2005 *Phys. Rev. Lett.* **94** 212302
[17] S. Di Matteo, L. Sperandio, VIP Note, IR-04, 26 April 2006; The energy shift has been computed by P. Indelicato, private communication.
[18] CCD-55 from EEV (English Electric Valve), Waterhouse Lane, Chelmsford, Essex CM1 2QU, UK.
[19] T. Ishiwatari et al. 2006 *Nucl. Instrum. Methods Phys. Res. A* **556** 509
[20] S. Bartalucci et al.(VIP Collaboration) 2006 *Phys. Lett. B* **641** 18
[21] I. Duck and E. C. G. Sudarshan 1998 *Am. J. Phys.* **66** 284